Energy-aware Data Gathering and Routing Protocol Based on Double Cluster-heads

Feifei Li, Xi Wang, Tingrong Xu
School of Computer Science & Technology, Soochow University
lifeifei198512@gmail.com

***Abstract*—this paper proposed an Energy-aware Data Gathering Protocol Based on Double Cluster-heads protocol (EAGRDC). In EAGRDC, the residual energy of sensor nodes and the average residual energy of node are compared to select the main structure of each cluster the cluster head. Then in the cluster structure, a vice cluster head is added in the cluster to responsible for data forwarding, thus it can unload part of the energy consumption of the main cluster head. When routing between clusters, a layer structure is used to seek the next hop node. The experiment results showed that, compared to LEACH and EADEEG, EAGRDC can effectively extend the time of death of node 30 rounds, and its number of cluster head is the most stable, thus it can significantly prolong the lifetime of network.**

Keywords—energy-aware; double cluster-heads; clustering; routing; wireless sensor network

I. INTRODUCTION

Wireless sensor networks [1,2] are deployed in the monitoring area by the large number of cheap micro-sensor nodes, wireless communication through the formation of a multi-hop's self-organizing network system, which aims to collaborate perception, acquisition and processing of network coverage area in the perception of objects, and forwarded to the observer process. It's the physical world and the objective logic of the information on the organic world together, thus changing the traditional way Exalted and natural interaction. As the number of nodes in large sensor networks, low cost and can be distributed in a wide range of areas and some people cannot reach the area, although the function of a single node is limited by the accuracy of the data collected is not high enough, but with a certain computing power by a large number, storage capacity and communications nodes to work together to form a high survivability of the network system to collect data to greatly enhance the accuracy and breadth of the returned data to reach the user decision-making criteria. Thus, the network system can be widely used in environmental monitoring and protection, national defense, disaster rescue, precision agriculture, traffic management, health care, intelligent buildings, intrusion detection, storage and tracking, and many other areas, causing a national academic, industrial community and the military departments of great importance.

Wireless sensor network is composed of numerous tiny, inexpensive and energy-constrained sensor nodes. The purpose of WSN is collecting, processing and transmitting information within the covered area [3]. However, because the number of sensor nodes is large, geographical distribution is wide, and the deployment of the regional environment is complex, even some regions the staff cannot reach, in wireless sensor networks, sensor node energy constraint becomes critical factor which directly determines the working life of the network. How to make efficient use of energy to maximize the lifetime of network is the most important issue of the sensor network, therefore, the chief design goal of wireless sensor network is to make efficient use of energy [4].

In wireless sensor network, the sensor data that collected by adjacent sensor nodes are often similar, and then there will be a lot of redundant information. In the data transmission process, data fusion before transmission can reduce the amount of data, and then greatly reduce energy consumption.

Clustering structure based on data aggregation method has been widely used in data collection protocols to reduce energy consumption and extend lifetime of network [5]. Cluster head nodes collect data and then use data fusion to reduce the amount of redundant data, and next send fused data to base station by other cluster head nodes. An energy-aware data gathering protocol based on double cluster-heads is proposed in this paper. EAGRDC (An Energy-Aware data gathering and routing protocol based on Double Cluster-heads for Wireless Sensor Networks) is a clustering-based data collection and routing methods. EAGRDC composed of double cluster heads structure [6], can reduce the energy consumption of the main cluster head, so that the frequency of the network nodes death can be reduced, thus effectively extending the network lifetime.

II. NETWORK MODEL AND PROBLEM DESCRIPTION

A. Network Model

First, we give the network model. The sensor network of N nodes randomly deployed in area A which is M×M square, all of the nodes periodically collect data, and assuming the wireless sensor network owns the characteristics as follows:

(1) The Sink node is unique, and it is located outside the observation area A. The sensor network is static, which is the locations of sensor nodes and sink node cannot move after deployment.

(2) Except sink node, all other nodes are homogeneous, and have the function of data fusion. Each node is assigned a unique ID number.

(3) Sink node energy is not restricted, while the energy of other nodes cannot be replenished.

(4) According to the distance of recipient, the node can freely adjust its transmit power to save energy consumption.

(5) The links between nodes are symmetric. If the nodes know each other's transmit power, according to the strength of received signal, they can computer the distance from the sender node approximate to themselves through RSSI.

B. Problem Description

For large-scale sensor networks, the network routing protocols are generally divided into two different categories form the aspect of architectures: plane routing protocol [7] and clustering-based routing protocol [8].

In plane routing protocol, each node is equal, there is no grades and levels, so structure maintenance work is not necessary, meanwhile, the status of network nodes are equal, then the probability of bottleneck effect is small, so plane routing protocol is simple, easy to extend, and owns good robustness. However, because there is no management node in plane routing protocol, the communication resource cannot be well managed and the data of neighboring nodes cannot fuse orderly.

In the clustering-based routing protocol, the network is often divided into clusters. A cluster consists of a cluster head and cluster member. Cluster head node collects data of the cluster members. After processes the data, the cluster head sends the results to the sink node.

LEACH (low-energy adaptive clustering hierarchy) [9] is a clustering-based distributed self-organization protocol. It proposes a clustering-based protocol for transmitting data to the base station. LEACH is the earliest clustering-based routing protocol proposed in WSN. It selects cluster head node randomly, and non-cluster head nodes transfer data to cluster head nodes, after the data fusion, cluster heads send the data to Sink.

EADEEG [10] proposed a clustering-based data collection protocol that solves the problem of energy heterogeneous in LEACH algorithm. The protocol adopts an energy aware clustering parameter and effectively solves the problem, thus EADEEG extends the network lifetime. However, due to the clustering structure, cluster heads are not only responsible for collecting data from other nodes and data integration, but also in charge of transmitting the data to sink, so the energy consumption of cluster head is much larger than the general node. If the energy consumption of cluster head node is fast, will increase the frequency that number of death nodes appear, and then lead to the failure of the entire network. For this problem, we propose EAGRDC (An Energy-Aware data gathering protocol based on Double Cluster-heads for wireless sensor networks), as shown in Figure 1, this protocol select a master cluster head MCH (Master Cluster Head) and a vice cluster head VCH (Vice Cluster Head) in a cluster, MCH is responsible for collecting information and data fusion, and VCH transmitting the data out. In the protocol, because MCH and VCH work together, they greatly reduce the energy consumption of the master cluster head, balance the load across the network, and thus extend the life of the network.

III. EAGRDC Design and Implementation

Since the energy consumption of each cluster is different, the method that re-selects the cluster head according to the energy threshold is of great instability.

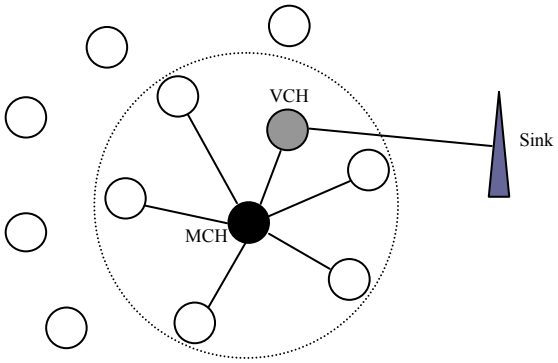


Figure1. The structure of Double Cluster-heads

If in a cluster, the initial energy of all nodes is relatively low, then the energy of cluster head will soon be below the threshold, but other clusters are still plenty of energy, the immediately re-election of cluster head is not conducive to the entire network. Therefore, EAGRDC runs by rounds, as shown in Figure 2, each round is divided into three stages: cluster setup(CS), routing and data transmission.

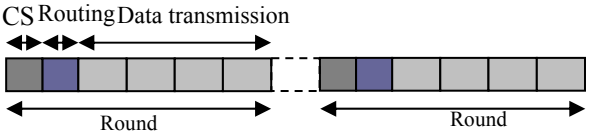


Figure2. The stages of round in EAGRDC

A. The Formation of Clusters

In the protocol of EADEEG, it proposed a method that the nodes compete for the cluster head. It uses the average residual energy of neighbor nodes and the ratio of their remaining energy as the main parameters, and this method can make the distribution of the cluster more uniform and effectively prolong the network lifetime. Regarding the problem that cluster heads consume energy excessively, this paper adopt a double cluster-heads structure, which can effectively share the energy consumption of cluster head, and avoid the cluster head node become dead node due to excessive energy consumption.

Firstly, the protocol selects MCH according to the residual energy of neighbor nodes. Each node of the network saves a neighbor table to store the information of neighbor nodes. In the beginning of each round, all nodes broadcast the message RE_Msg by radius r. RE_Msg includes the ID of the node and its residual energy RE. The node updates ID value and the residual energy values of RE in its neighbor table according to the RE_Msg.

After all of the nodes update their neighbor tables; each node calculates the average residual energy of its neighbor nodes according to the value of the residual energy and distance. The average residual energy E_{ava} is computed as follows:

$$E_{ava} = \frac{\sum_{i=1}^{n} \left(E_{res} \cdot \frac{\sum_{i=1}^{n} d_i / n}{d_i} \right)}{n} \quad (1)$$

Where E_{res} denotes the value of residual energy of the neighbor node i, and d_i specify the distance from i to this node. Known that the energy consumption is mainly in transmission, so the node further away from other nodes is not suitable for cluster head, we add d_i as an impact factor. When the distance is further, the relative value of residual energy becomes lower, thus the time that the node competing MCH is longer.

Then come to the phase of electing MCH, each node in the network send the message of competing MCH at time t_1 or t_2 which is confirm by the formula(2)、(3):

$$t_1 = \frac{T_{MHD}}{2} \times \frac{E_{ava}}{E_r} \times \sigma, \qquad E_r \geq E_{ava} \tag{2}$$

$$t_2 = T_{MHD} - \frac{T_{MHD}}{2} \times \frac{E_r}{E_{ava}}, \qquad E_r < E_{ava} \tag{3}$$

Where T_{MHD} is the lasting time of electing MCH and it is preset. E_r is the residual energy of this node. σ is a real value distributed in [0.9,1] and it is randomly generated, its role is to reduce the probability that the two or more nodes sent the MCH competition message at the same time. From the formula (2) we can see, in the time slot T_{MHD} of the MCH competition, the majority of the MCH nodes are determined in the first $T_{MHD}/2$. In the period [$T_{MHD}/2$, T_{MHD}], the nodes which cannot become MCH nodes because of timeout and at the meantime cannot receive the message that send by other MCH nodes will be classified.

All the nodes calculate their own time t that sends MCH compete message CptMHD_Msg by formula (2) and (3). If the node did not receive the CptMHD_Msg sent from other nodes before their own time t, the node sends CptMHD_Msg to its neighbor nodes and declares they it becomes the MCH node; Otherwise, the node gives up the chance of competing MCH node, and according to the CptMHD_Msg that has been received, selects the MCH node with strongest signal to join and becomes its member.

After selecting the MCH, it comes to the phase of cluster formation. The MCH nodes broadcast MCH_Msg to their neighbor nodes, and when the non-MCH nodes receive the message, they response the MCH with the strongest signal.

Then it comes into the phase that selecting VCHs. The VCH nodes are selected by MCHs, and the MCH nodes assign the VCHs from the cluster members according to the formula (4).

$$M = \frac{E_{res}}{k \cdot d_i} \tag{4}$$

Where k is a number between [0, 1] which is pre-set, and the selection of VCHs is related to the residual energy value and the distance from MCH. The nodes with more energy and nearer to the MCHs have more priority to become VCHs.

B. Routing Algorithm

In our algorithm, VCHs are responsible for forwarding the data instead of the MCHs. Therefore, the set of VCHs will be set as a high layer of network for routing.

When data transfer between clusters, VCHs form data transmission path according to certain requirements or constraints and through the specific routing algorithm. This stage of data transfer is only carried out by the VCHs, and the statuses of VCHs are equal, so we can use the plane routing protocol. EAGRDC builds a layered system to routing between clusters. In the beginning of the system, all nodes are initialized and each node will be set a layer ID, denoted by LID. The value of node i's LID is decided by the distance from node i to the Sink node.

$$LID = \lfloor d_{i,\sin k} \rfloor \tag{5}$$

Where $d_{i,sink}$ is the distance between node i and Sink node. We can see from the formula (5) that the node closer to the Sink node, the LID is smaller.

As shown in Figure 3, if the nodes own the same LID, their distance from the Sink node is basically the same. In the protocol the data forwarding between clusters is responsible by the VCHs, and the VCH select the next hop routing node as follows:

Step1. When Sink node locates in the communication radius of VCH i, i communicate directly with Sink;

Step2. If Sink node doesn't locate in the communications radius of the VCH i, and i has neighbor VCH nodes whose LID are smaller than it, then i selects the nearest VCH in these VCHs as the next hop routing node;

Step3. If in the communication radius of VCH i, there are neither Sink node nor neighbor VCH nodes whose LID are smaller than i, the node i amplify its transmission radio, then turn to the step 1.

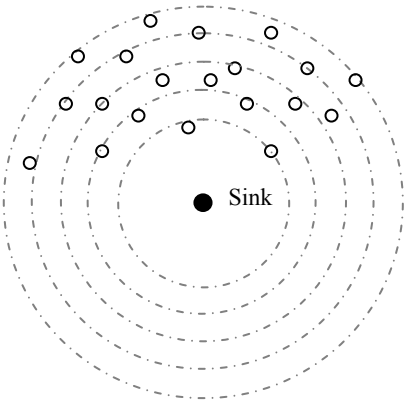


Figure 3 . The layer structure

As VCHs select only the nodes that the value of LID are smaller than their as the next hop routing node, it can effectively prevent the occurrence of the routing loop.

C. Data Transmission

After the data transmission path between VCHs and Sink node is established, ordinary nodes members in cluster begin to collect the data and sent it to the MCH, then the MCHs process the data on data fusion, and then they sent the fused data to their VCHs, then VCHs fuse the received data and their collected data, and then they send the fusion data to the Sink node along the multi-hop path established before.

IV. ANALYSIS OF ALGORITHM

According to the wireless communication theory [11], a wireless sensor node to transmit a k-bit message a distance d, the radio expends:

$$E_{Tx}(k,d) = E_{Tx_elec}(k) + E_{Tx_amp}(k,d) = \begin{cases} kE_{elec} + k\varepsilon_{fs}d^2, & d < d_o \\ kE_{elec} + k\varepsilon_{mp}d^4, & d \geq d_o \end{cases} \quad (6)$$

And the node to receive this message, the radio expends:

$$E_{Rx}(k) = E_{Rx_elec}(k) = kE_{elec} \quad (7)$$

Where E_{elec} denote the electronics energy, that is the energy consumption of transceiver circuit send or receive per bit data, $\varepsilon_{fs}d^2$ and $\varepsilon_{mp}d^4$ is the energy consumption of the amplifier that per bit of data is sent. If the transmission distance is less than the threshold value d_0, power consumption is proportional to the square of the distance, and if the transmission distance is greater than d_0, power consumption is proportional to the fourth power of distance.

It can be seen from the energy consumption formula (6), if the data collecting, data fusion and then forwarding out are only processed by the MCHs, the MCH is not only responsible for data fusion but also in charge of forwarding data between clusters, it would cost large energy, and the MCH nodes will soon run out of energy and become dead nodes. To address this issue, the Double Cluster-heads mechanism introduces the VCH. The VCH takes over the data forwarding between clusters which will consume lots of energy of MCH, then the energy of MCH can be saved efficiently, thereby the frequency of dead nodes are reduced and the network lifetime is extended.

When the MCHs collect the data from nodes in cluster, the VCHs needn't sent their own data to the MCHs, and when they receive the fusion data that send by MCHs, they fuse the received data with their own data. Thus it can avoid the energy consumption caused by duplication of data send.

While it takes certain energy in the selection of vice cluster head, but it can still be acceptable if we use a small amount of energy to exchange the extending of the lifetime of the entire network.

In EAGRDC data collection protocol, all nodes in the network are involved in the MCH competition, which is conductive to elect the optimal node as the MCH. The competition of MCH is not only effected by the residual energy of neighboring nodes, but also taking into account the distance between the node and its neighboring nodes, and adding the concept of layers in the inter-cluster routing, the vice cluster head nodes choose the best neighboring vice cluster to be the next hop node for routing.

In the following, we analysis and prove the covering domain of the MCH election algorithm, time complexity message complexity and other performance evaluation for EAGRDC protocol.

(1) According to formula(2) and (3), we can compute the moment that nodes send the message to compete MCH, and the result meets the inequality: $t_1<T_{MHD}/2<t_2<T_{MHD}$.

Proof. If the residual energy of the node is satisfied $E_r \geq E_{ava}$, there is $\frac{E_{ava}}{E_r} \times \sigma \leq 1$, then $\frac{T_{MHD}}{2} \times \frac{E_{ava}}{E_r} \times \sigma \leq \frac{T_{MHD}}{2}$, that is $t_1 \leq \frac{T_{MHD}}{2}$. When the node energy is satisfied $E_r < E_{ava}$, $\frac{E_r}{E_{ava}} < 1$, then $0 < \frac{T_{MHD}}{2} \times \frac{E_r}{E_{ava}} < \frac{T_{MHD}}{2}$, $\frac{T_{MHD}}{2} < T_{MHD} - \frac{T_{MHD}}{2} \times \frac{E_r}{E_{ava}} < T_{MHD}$, in order $\frac{T_{MHD}}{2} < t_2 < T_{MHD}$.

From the above we can conclude that $t_1<T_{MHD}/2<t_2<T_{MHD}$.

(2) The coverage domain of MCH election algorithm is 100%.

Proof. The above proof shows that when nodes compete MCH, $t_1<T_{MHD}/2<t_2<T_{MHD}$, the maximum time for competing MCH is T_{MHD}. In former $T_{MHD}/2$ period, the node whose residual energy is greater than average residual energy of its neighbor nodes accesses to the moment sending the MCH competition message. These nodes either become the MCH node, or give up the competition to become the members of other MCH node. And in the period [$T_{MHD}/2$, T_{MHD}], the node whose residual energy is less than the average residual energy of its neighbor nodes and also not be in the cluster radius of other MCH node send the message stating that it becomes a MCH node. So we can conclude that the coverage domain of MCH election algorithm is 100%.

(3)The sum of energy consumption of the network protocol in EAGRDC protocol << the sum of energy consumption of the network protocol in LEACH protocol.

Proof. Wireless communication model shows that the gap of energy consumption between different routing strategy is mainly in sending data, and the energy consumption of a single node sending 1bit data as follows:

$$E_{mem} = \begin{cases} E_{elec} + \varepsilon_{fs} d^2, & d < d_o \\ E_{elec} + \varepsilon_{mp} d^4, & d \geq d_o \end{cases} \quad (8)$$

As the nodes choose the nearest MCH node to join when the cluster forming, the energy consumption of a member node when it sends data to MCH nodes is:

$$E_{mem} = E_{elec} + \varepsilon_{fs} \cdot d^2 \quad (9)$$

It can be seen that the sum of energy consumption of the ordinary member nodes in EAGRDC protocol and in LEACH protocol is basically the same. However, in inter-cluster routing, VCH nodes choose the nearest neighbor VCH to forward in EAGRDC. Assuming that the average per-hop distance is d_1 ($d_1 > d_0$), and VCH forwards the data through n times to reach the Sink node, then the energy consumption is:

$$E_{VCH} = n \cdot E_{elec} + n \cdot \varepsilon_{fs} \cdot d_1^2 \quad (10)$$

In LEACH protocol, cluster head nodes send data to Sink node through one hop, under the same circumstances, the energy consumption of cluster head nodes is:

$$E_{CH} = E_{elec} + \varepsilon_{mp} \cdot (n \cdot d_1)^4 \quad (11)$$

Since $E_{CH} / E_{VCH} \approx n^3 d_1^3$, therefore $E_{VCH} << E_{CH}$, then $E_{EAGRDC} << E_{LEACH}$.

(4) The time complexity of EAGRDC algorithm is O (1).

Proof. The execution time of the algorithm includes the network initialization, neighbor discovery, the competition of MCH, ordinary nodes join in and the selection of VCH, the establishment of inter-cluster routing, in which, the time overhead of neighbor discovery, ordinary nodes join in and the selection of VCH is equal to the time that wireless signal transmission by distance *r*, the time of MCH competition is T_{MHD}, and the time overhead that VCH nodes establish inter-cluster forwarding routing is also fixed. Therefore, the time complexity of EAGRDC algorithm is O (1).

(5) The message complexity of EAGRDC algorithm is O (*N*).

Proof. At the beginning of each round, each node needs to send *N* StatusMsg message, later the *M* nodes which became MCH nodes need to send *M* ClusterMsg message, and each ordinary node sends *N-M* JoinMsg message, and then MCH nodes need to send *M* CVCH_Msg message to selecting VCH nodes , and each number of TDMAMsg, RouteFindMsg, RouteReplyMsg is *M*. Therefore, the total number of messages is $N+M+N-M+4\times M=2N+4M$, because *M* is much smaller than *N*, so the message complexity of EAGRDC algorithm is O (*N*).

V. SIMULATION AND ANALYSIS OF THE RESULTS

To evaluate the performance of EAGRDC algorithm, our simulation work attempts to compare the performance of EAGRDC against LEACH and EADEEG, and the simulation environment is set as follows:

We use OMNeT + + 3.3 version as the simulation tool. The network deployed in the area of 100 × 100, and 100 nodes are randomly distributed in the region, besides Sink node position is fixed. The parameters are shown in TABLE Ⅰ.

As shown in Figure 4, in the same situation of the network deployment, with the increase of the round, the number of remaining alive network nodes of three algorithm show different trends. With the increase of rounds, our proposed algorithm EAGRDC has better performance than other two algorithms. This is because we adopted the VCH which can unload part of energy consumption of the MCH. The figure shows, EAGRDC algorithm will share power more evenly to each node, so that the number of rounds that the first dead node appear is longer than EADEEG about 30, so it can effectively improve the network life cycle.

TABLE I. PARAMETERS SETTING

Parameter	Value
Network scale	100×100
Position of Sink node	（110,100）
Number of sensor nodes	100
Sense scale	10
E_{elec}	50nJ/bit
ε_{fs}	10pJ/bit/m2
ε_{mp}	0.0013pJ/bit/m2

It can be seen from Figure 5, in EAGRDC algorithm, the number of cluster head is the most stable, the number in each round is maintained at 20 or so. In the LEACH protocol, the cluster head node is chosen randomly, so the number of cluster heads is the most unstable. In EADEEG agreement, the energy consumption of the cluster head node is large, so the number of cluster head that chosen according to neighbor residual energy is not stable. The stability of the number of cluster head reflects the data that network receive and send is roughly the same, consequentially, it can ensure the collection of information and reliability of the network.

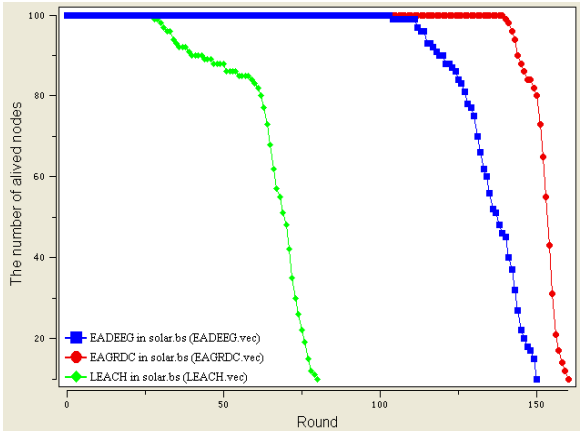


Figure4. The number of alived node

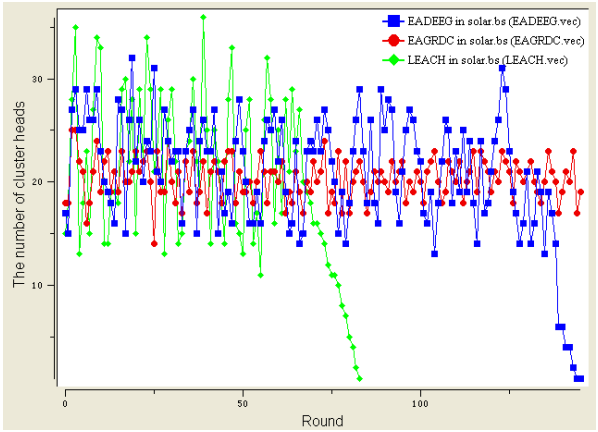


Figure5. The number of cluster head node

In the hierarchical routing protocols, cluster head nodes not only collect data but also forward data between clusters, so cluster head nodes are most likely to run out energy prematurely. In the EAGRDC, the vice cluster head nodes are responsible for forwarding data between clusters, thus greatly reducing the energy consumption of the main cluster heads. Figure 6 depicts the sum of energy consumed by cluster heads in the different protocol.

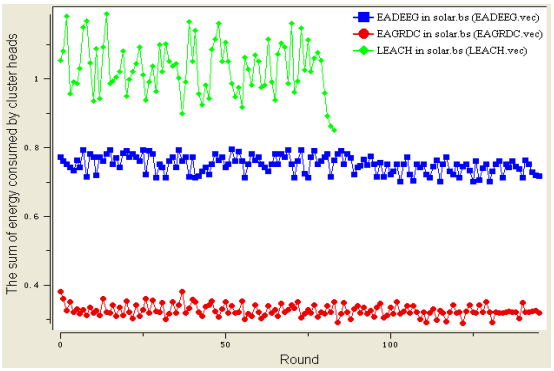


Figure6. The sum of energy consumed by cluster heads

Figure 7 shows the energy consumption of the network. Compare to LEACH, EAGRDC can save about 30 percent of energy. And the energy consumption of EAGRDC is a bit larger than EADEEG. This is because in the choice of VCH, it needs to spend some energy, but it is acceptable that we use a small amount of energy consumption to exchange for the extension of the entire network life cycle in terms of the entire network.

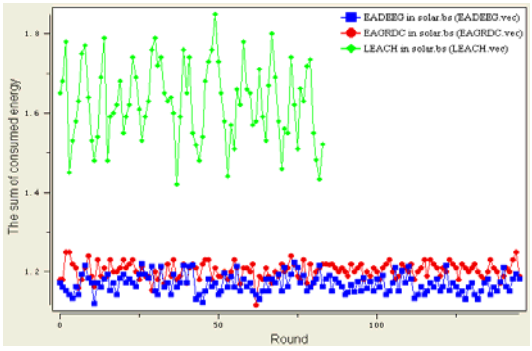


Figure7. The sum of consumed energy

VI. CONCLUSIONS

To extend the lifetime of wireless sensor networks, we propose an energy-aware data gathering and routing protocol EAGRDC based on Double Cluster-heads. In the cluster, vice cluster head is introduced to forwarding the fusion data between clusters and it can share the energy consumption of the main cluster head. When data transfer between clusters, we used a layer structure to seek the next hop node. According to this method, the frequency of the cluster head become death node can be reduced, thus the network lifetime is effectively extended.

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